Information and the problem of biological organization: Between thermodynamics and biology

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The second law of thermodynamics is often colloquially interpreted as a law of the inevitable increase of disorder, although in a strict sense it refers to the statistical behaviour of entropy in isolated systems. From this perspective, the emergence and long-term maintenance of complex organisation in open systems require a special explanation. A classical point of reference here is the paradox of Maxwell's demon, which shows that a local decrease in entropy may be achieved not through the supply of additional energy, but through the selective regulation of the course of physical processes. This paradox reveals a fundamental distinction between energy balance and the organisation and control of a system's dynamics. Contemporary analyses of Maxwell's demon, however, demonstrate that regulation is not a cost-free process. In order to select microstates, the demon must collect, process, and erase information, which entails unavoidable thermodynamic consequences. Claude Shannon's information theory and Landauer's principle reveal a close connection between information and entropy: information is not an energetic quantity, yet its processing requires physical realisation and is subject to the laws of thermodynamics. In this sense, information constitutes an intermediate concept – irreducible both to purely abstract formal structures and to energetic quantities alone – describing physically realised constraints and possibilities for the regulation of processes. This perspective acquires particular significance in biology. Living organisms function as systems far from thermodynamic equilibrium, capable of maintaining stable organisation through the precise regulation of internal processes. Biological information plays a central role here: it is physically encoded and employed in the regulation of cellular processes. The genetic code, described by Erwin Schrödinger as an "aperiodic crystal", constitutes a physical realisation of processes of information encoding and decoding, whose purely energetic description, though necessary, proves insufficient to capture their regulatory and organisational functions. A similar intuition was articulated by Hans Driesch, who argued that energy conservation alone is insufficient to explain biological organisation and postulated a non-energetic regulatory factor (entelechy). Although no longer a scientific hypothesis, this concept serves as a historically significant heuristic pointing to the problem of regulation irreducible to energy balance. From this perspective, both the paradox of Maxwell's demon and Hans Driesch's concept of entelechy do not constitute alternative theories of nature, but rather serve as heuristic indicators of the limits of explanations based solely on energy balances. In both cases, it becomes apparent that the key problem is not the source of energy itself, but the manner in which processes are organised and regulated over time. Contemporary physics of information shows that such regulation is not "free": it requires the physical realisation of information and entails unavoidable entropic costs, even though it cannot be reduced to a simple transfer of energy. In this sense, the question posed by Erwin Schrödinger – "What is life?" – does not call for an answer in the form of a new substance or a special kind of energy, but points instead to the problem of organising physical processes capable of sustaining ordered structure far from equilibrium over time. Information appears here not as an ontological entity, but as a descriptive category that makes it possible to grasp physically realised constraints and possibilities for regulating the dynamics of biological systems. As a bridging concept between physics and biology, it allows life to be interpreted as a process of regulated organisation, consistent with the second law of thermodynamics and yet irreducible to energy balance alone.

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